



Sustainable Transportation Energy Pathways (STEPS)

IS NG A “BRIDGE” TO H₂ TRANSPORTATION FUEL?

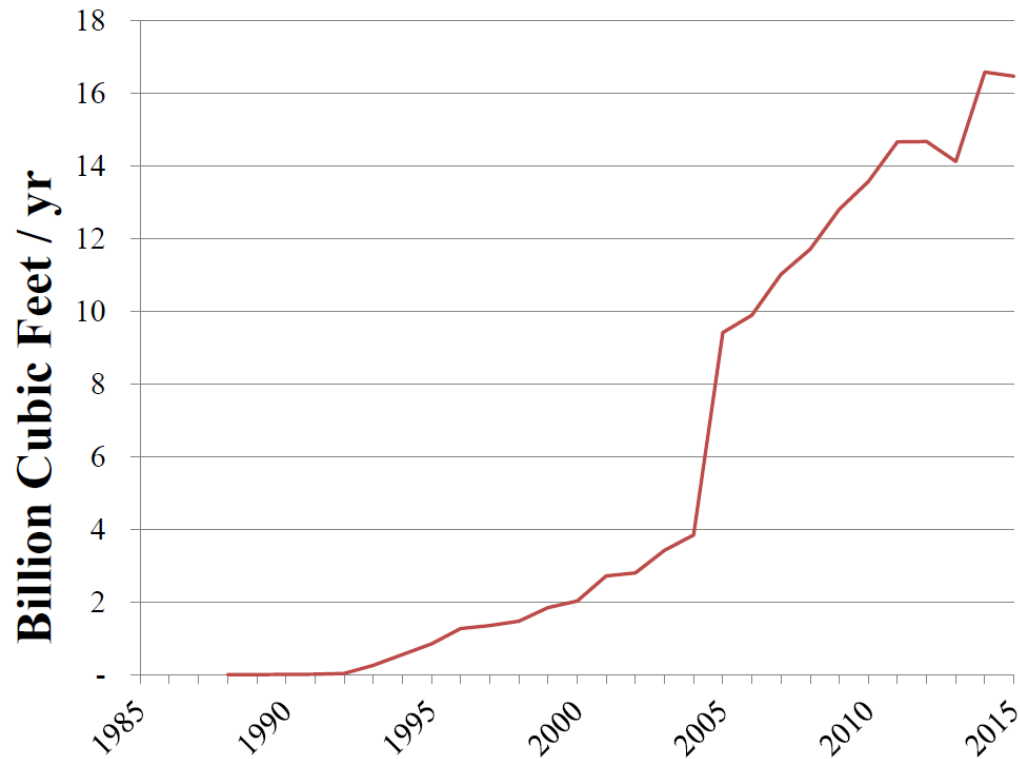
July 18, 2017

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Presented at the
California Air Resources Board Research Seminar

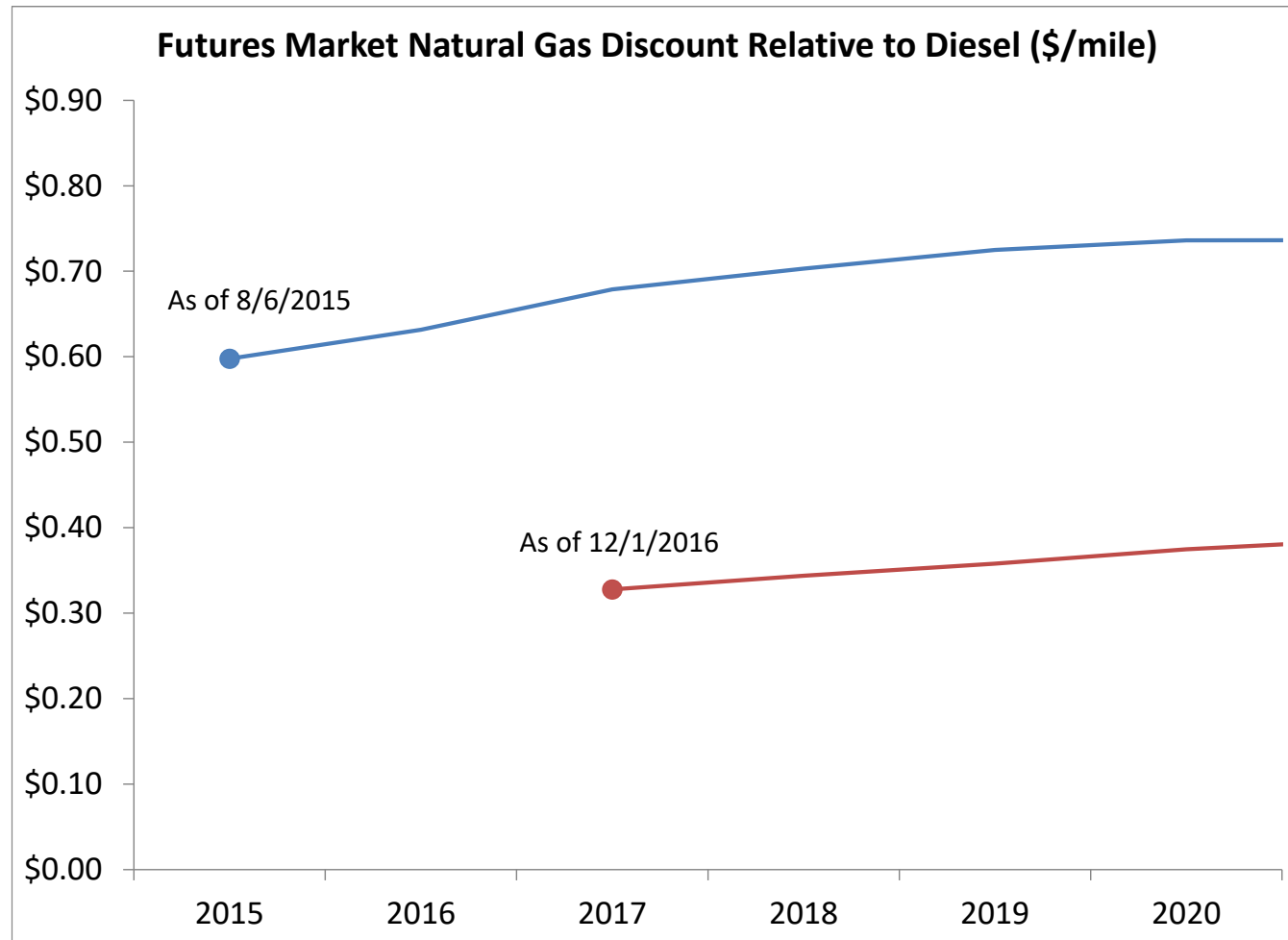
Natural Gas small but growing fuel source

CA Vehicular Nat Gas Consumption



Source: EIA

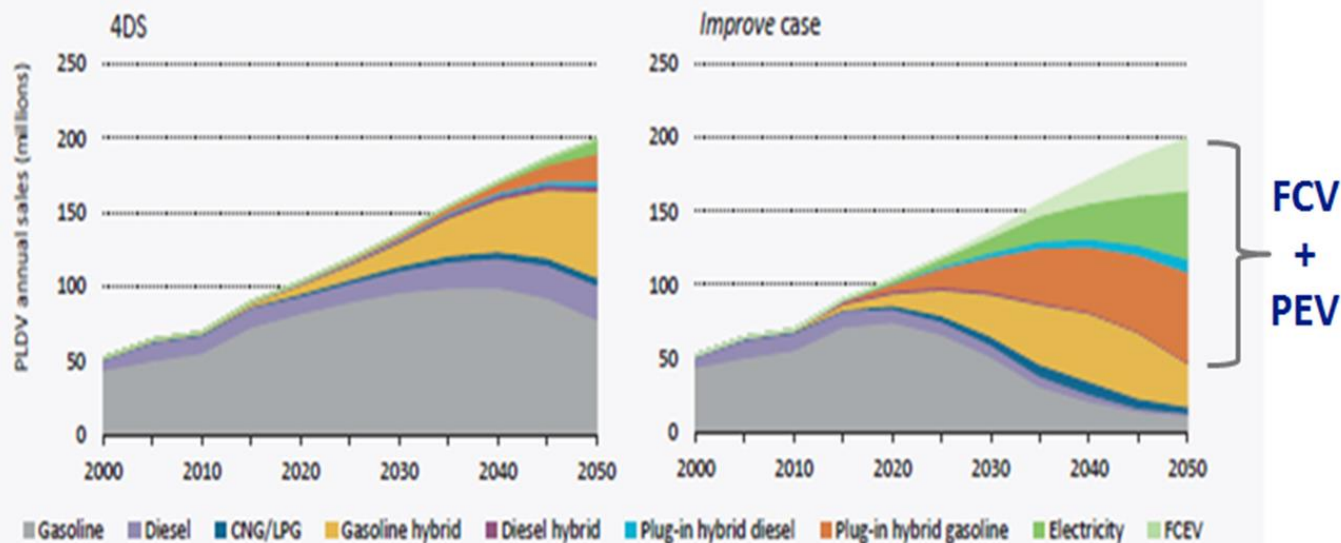
Natural Gas Price Discount Relative to Oil



Source: CME Group

LIGHT DUTY VEH: ROLE OF NG, H2 IN DEPENDS ON LONG TERM CARBON GOALS (4° & 2 ° scenarios-IEA)

Figure 13.18 Global portfolio of technologies for passenger LDVs



Key point

In the Improve case, electric, PHEV and FCEVs together account for nearly three-quarters of new vehicle sales in 2050.

Source: International Energy Agency, Energy Technology Perspectives, 2012.

QUESTIONS: NG as a “Bridge” to H2 Transportation Fuel?

- What are the likely roles of natural gas and H2 in various transport applications?
- What infrastructure options could supply NG or H2 to vehicles? Could a future H2 refueling infrastructure grow “organically” from NG refueling infrastructure? Could NG equipment be repurposed or designed for future H2 compatibility?
- How might the growth of natural gas and H2 transportation markets impact infrastructure development and synergies? How much might natural gas and hydrogen infrastructures “overlap” geographically and over time?
- What are the technical issues for using hydrogen or hydrogen blends in the natural gas system? When is blending renewable hydrogen (“power to gas”) into natural gas an attractive path toward carbon-free hydrogen transportation?

Transportation Applications for H2 and NG

H2 dominates light duty; LNG long haul

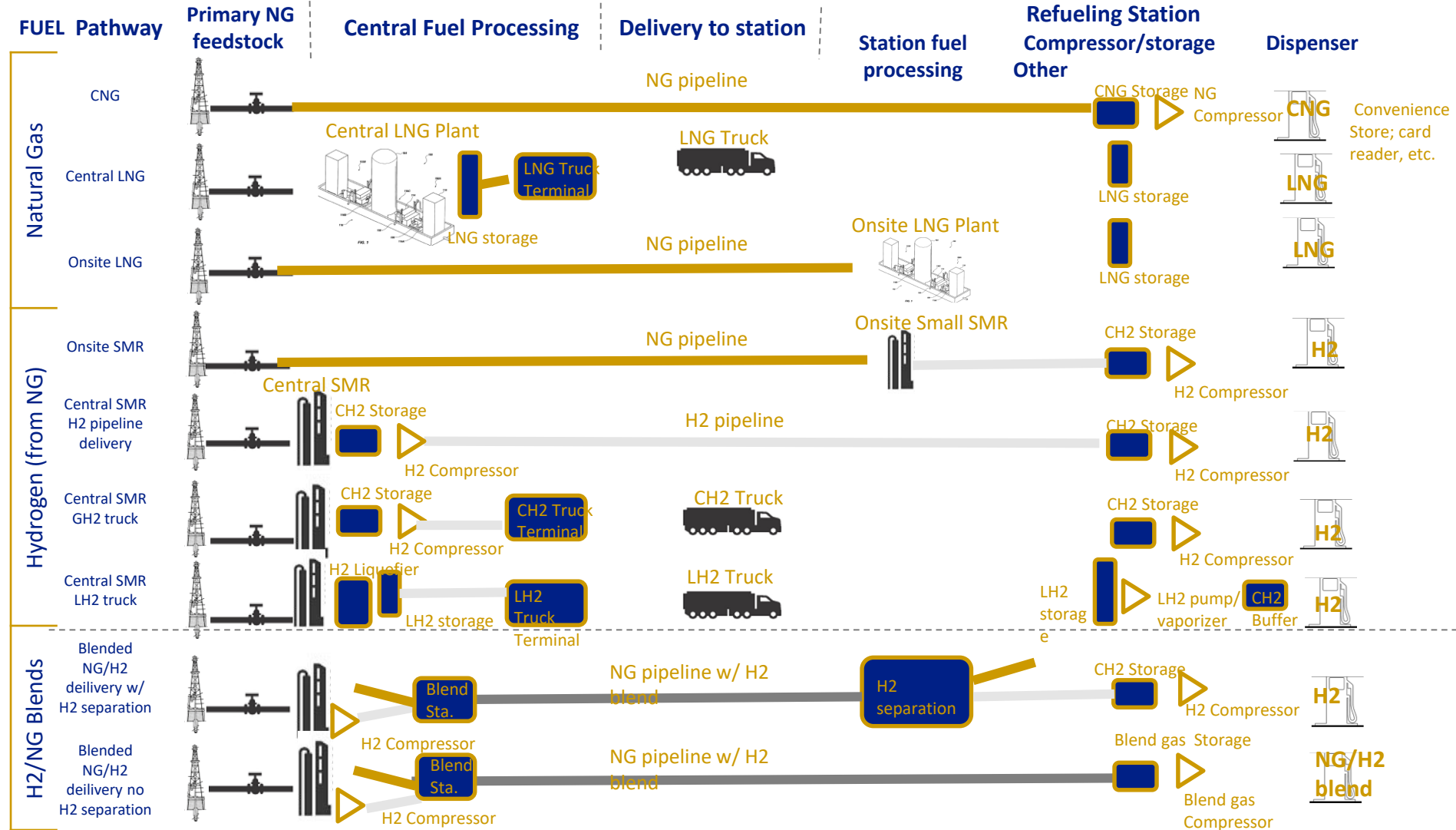
Most potential overlap is for fleets, buses and trucks.

Table 1. Transportation Applications for Natural Gas and Hydrogen^a

Application	NG		H2	
	<i>CNG</i>	<i>LNG</i>	<i>CH2</i>	<i>LH2</i>
LIGHT DUTY VEHICLES	X		X	
BUSES	X		X	
MED DUTY TRUCKS	X		X	
HEAVY DUTY TRUCKS	X	X	X	X
RAIL		X		X
MARINE		X		X
AVIATION		X		X

CNG = compressed natural gas; LNG = liquefied natural gas; CH2 = compressed hydrogen gas;
LH2 = liquid hydrogen

NG and H2 SUPPLY PATHWAYS



Supply chain synergies for NG & H2 transport fuels

FUEL	Pathway	Primary feedstock	Central Fuel Processing			Delivery to station		Refueling station					
								Station fuel processing		Compression/ Storage		Dispenser	Other
Natural Gas	CNG	NG via pipeline				NG pipeline		Dryer/filter		NG compressor;	CNG storage	CNG dispenser	Card reader, convenience store, etc.
	Central LNG	NG via pipeline	Dryer/filter;	NG Liquefier;	LNG Cryo storage	LNG truck terminal	LNG Truck			LNG storage		LNG dispenser	Card reader, convenience store, etc.
	Onsite LNG	NG via pipeline				NG pipeline		Dryer/filter;	Small NG Liquefier (LNG in a box)	LNG storage		LNG dispenser	Card reader, convenience store, etc.
Hydrogen (from NG)	Onsite SMR	NG via pipeline				NG pipeline		Dryer/filter;	Small SMR	CH2 compressor; CH2 storage		CH2 dispenser	Card reader, convenience store, etc.
	Central SMR H2 pipeline delivery	NG via pipeline	Dryer/filter;	SMR; H2 compressor	bulk GH2 storage;	H2 pipeline				CH2 compressor; CH2 storage		CH2 dispenser	Card reader, convenience store, etc.
	Central SMR GH2 truck	NG via pipeline	Dryer/filter;	SMR; H2 compressor	bulk GH2 storage;	GH2 truck terminal	GH2 truck			CH2 compressor; CH2 storage		CH2 dispenser	Card reader, convenience store, etc.
	Central SMR LH2 truck	NG via pipeline	Dryer/filter;	SMR; H2 Liquefier	bulk LH2 storage;	LH2 truck terminal	LH2 truck			LH2 pump/ vaporizer ; LH2 storage;	CH2 biuffer storage	CH2 dispenser	Card reader, convenience store, etc.
H2/NG Blends	Blended NG/H2 deilivery w/ H2 separation	NG via pipeline	Dryer/filter;	SMR; H2 compressor	bulk GH2 storage; blend station to add H2	NG pipeline (w/blend H2)		H2 Separation equipment		CH2 compressor; CH2 storage		CH2 dispenser	Card reader, convenience store, etc.
	Blended NG/H2 deilivery no H2 separation	NG via pipeline	Dryer/filter;	SMR; H2 compressor	bulk GH2 storage; blend station to add H2	NG pipeline (w/blend H2)				Blend gas compressor; Blend gas storage		Blend gas dispenser	Card reader, convenience store, etc.

POTENTIAL OVERLAP: compressors & gas storage in CNG & H2 sta.
H2 and H2/NG blends in NG pipelines

H2 INFRASTRUCTURE TRANSITION

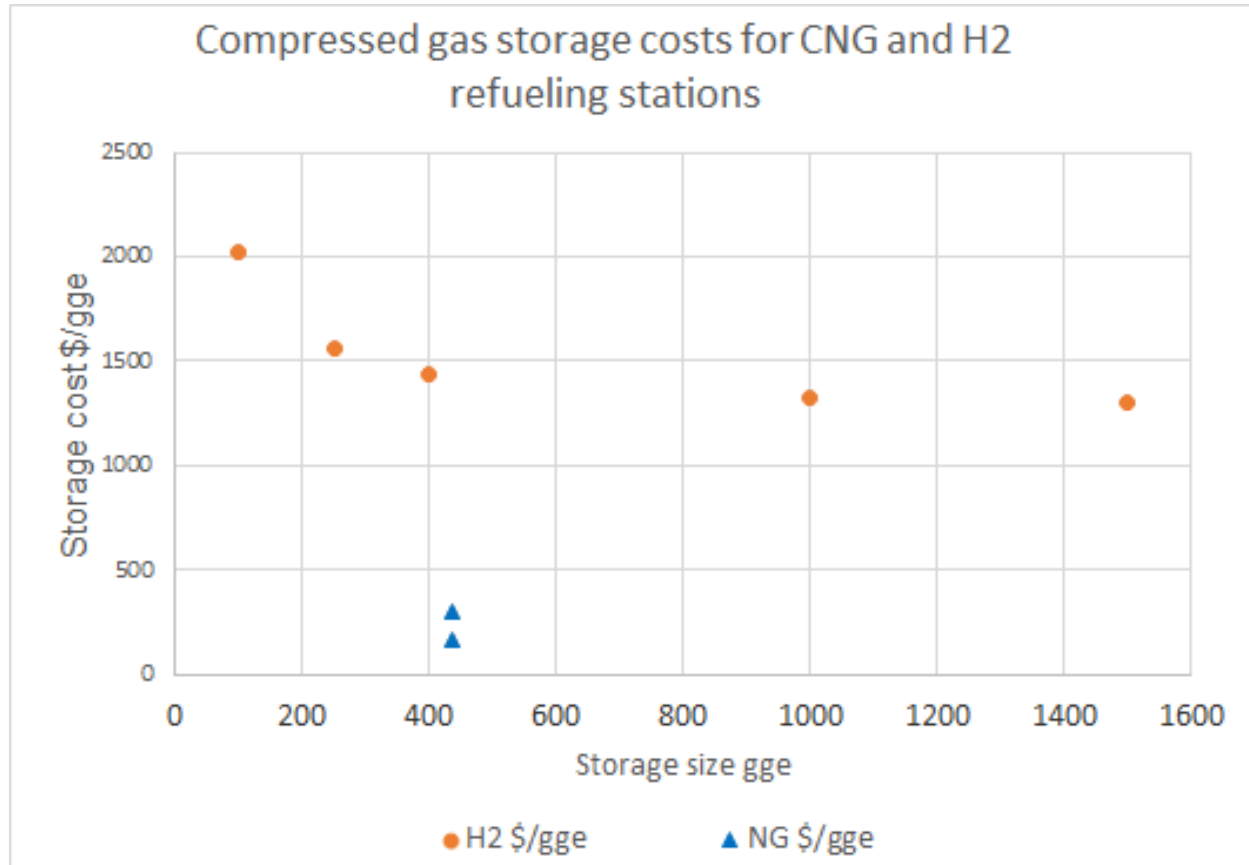
H2 TRANSPORTATION FUEL INFRASTRUCTURE GROWS “ORGANICALLY” OUT OF NG INFRASTRUCTURE:

- 1) overbuild or re-purpose CNG stations for future use with H2
- 2) blend renewable hydrogen into NG pipeline system (“power to gas” concept) where electrolytic H2 is produced from curtailed variable renewable electricity

BUILD DEDICATED H2 REFUELING INFRASTRUCTURE

(phase out NG over time?)

OVERBUILDING CNG STATIONS FOR FUTURE H2 COMPATIBILITY IS NOT ECONOMICALLY ATTRACTIVE



H2 Storage several times as expensive as CNG storage.

Difficult to recover the extra cost of building for H2 compatibility- unless the station was forced to switch to H2 within 3 years.

MAGNITUDE & TIMING OF NG & H2 VEHICLE MARKETS IN CA TRANSITION SCENARIO TO 2035 (Miller et al. 2017)

SCENARIO TO 2035 FOR CALIFORNIA MARKET GROWTH OF

- H2 FCV light duty vehicles
- LNG for long haul trucks
- H2 FCVs and CNG in fleet trucks, buses

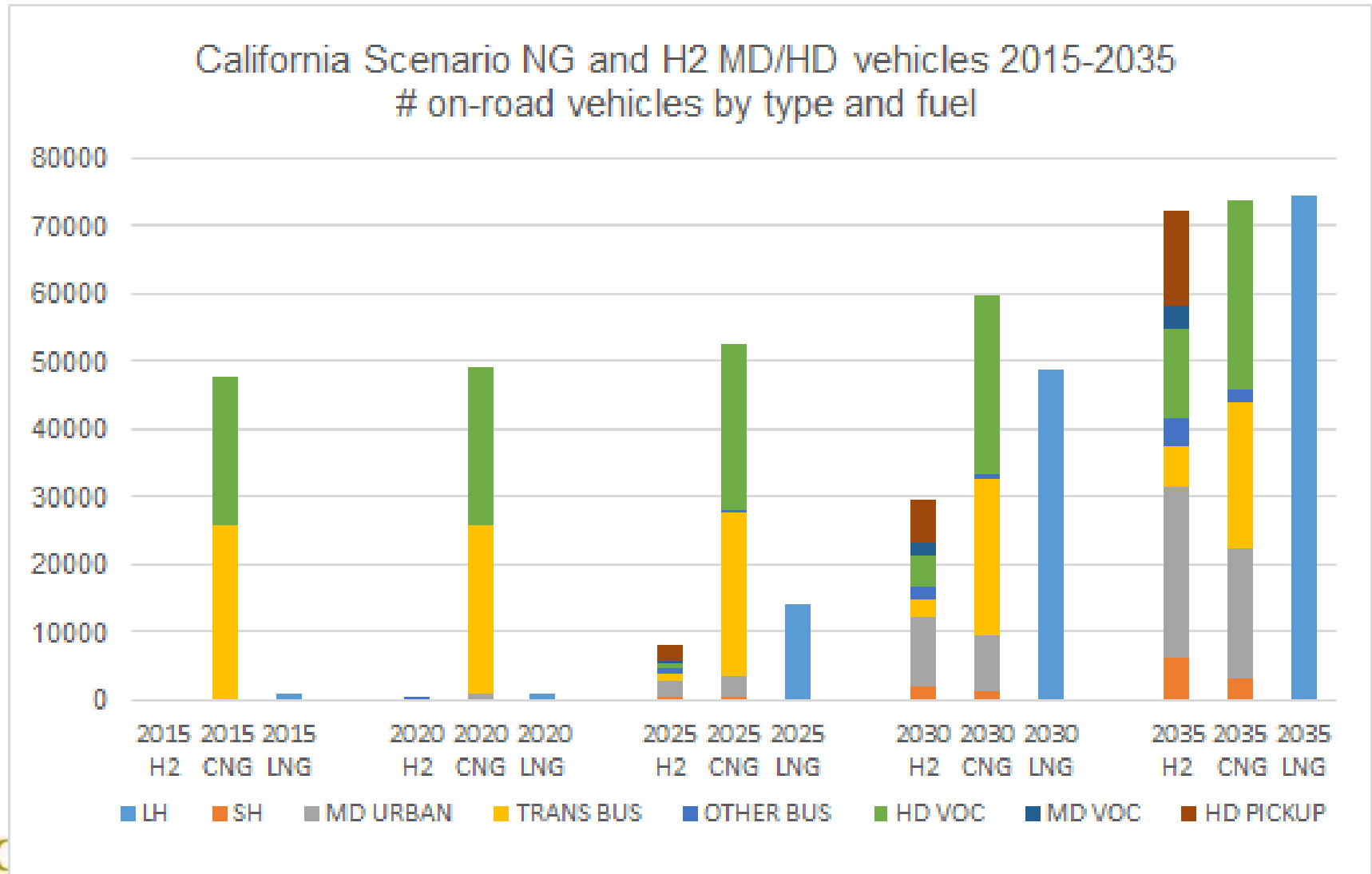
ESTIMATE INFRASTRUCTURE BUILDOUT FOR EACH APPLICATION

- Fuel dispensed, size, type, number of stations
- Spatial layout of networks (overlap?)
- Timing for building stations

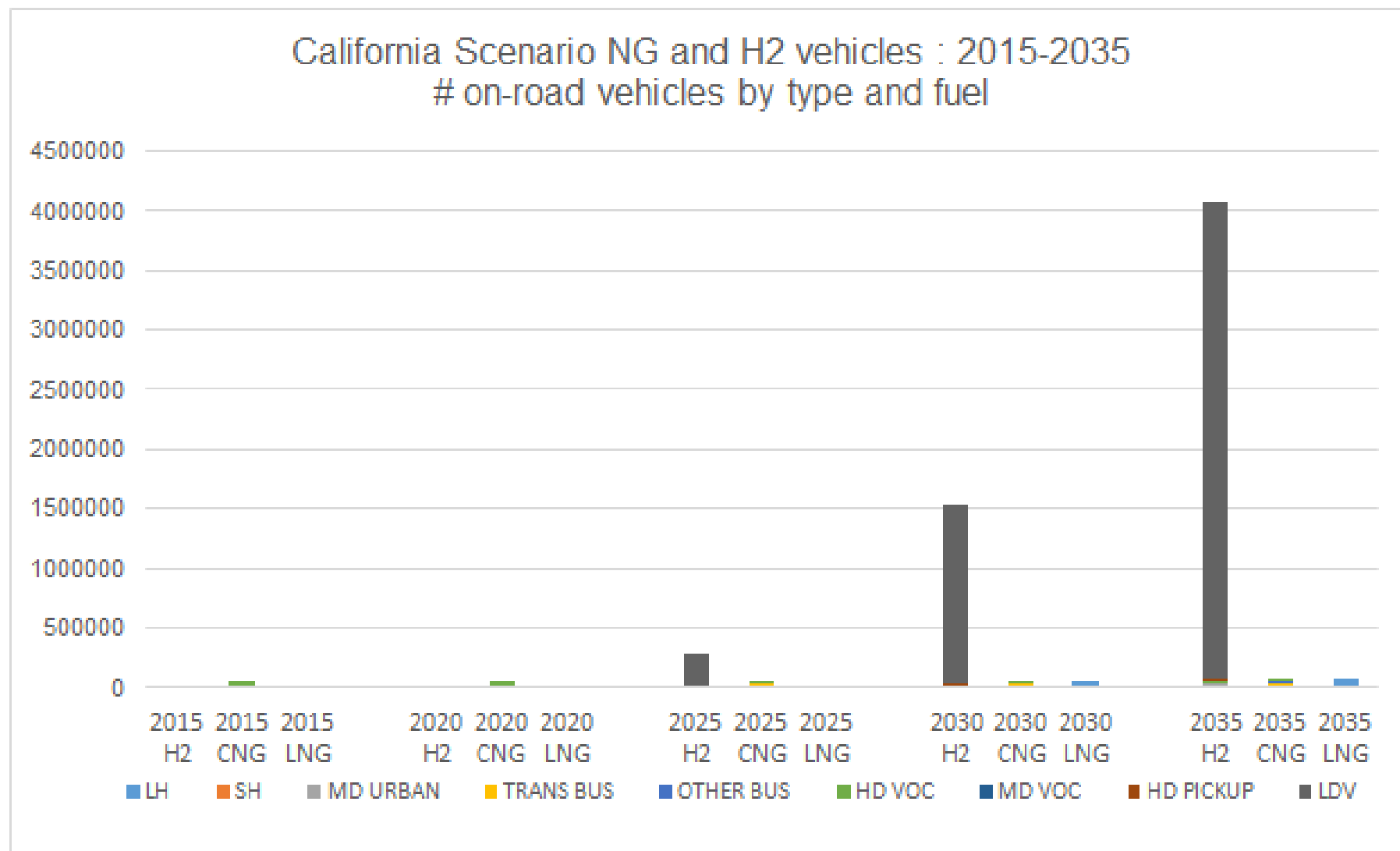
CA MEDIUM/HEAVY DUTY SCENARIO (Miller et al.):

LNG Grows as Fuel for Long Haul Trucks (>2025);

H2 (>2025), CNG as Fuels for Buses, MD Trucks, Drayage Trucks

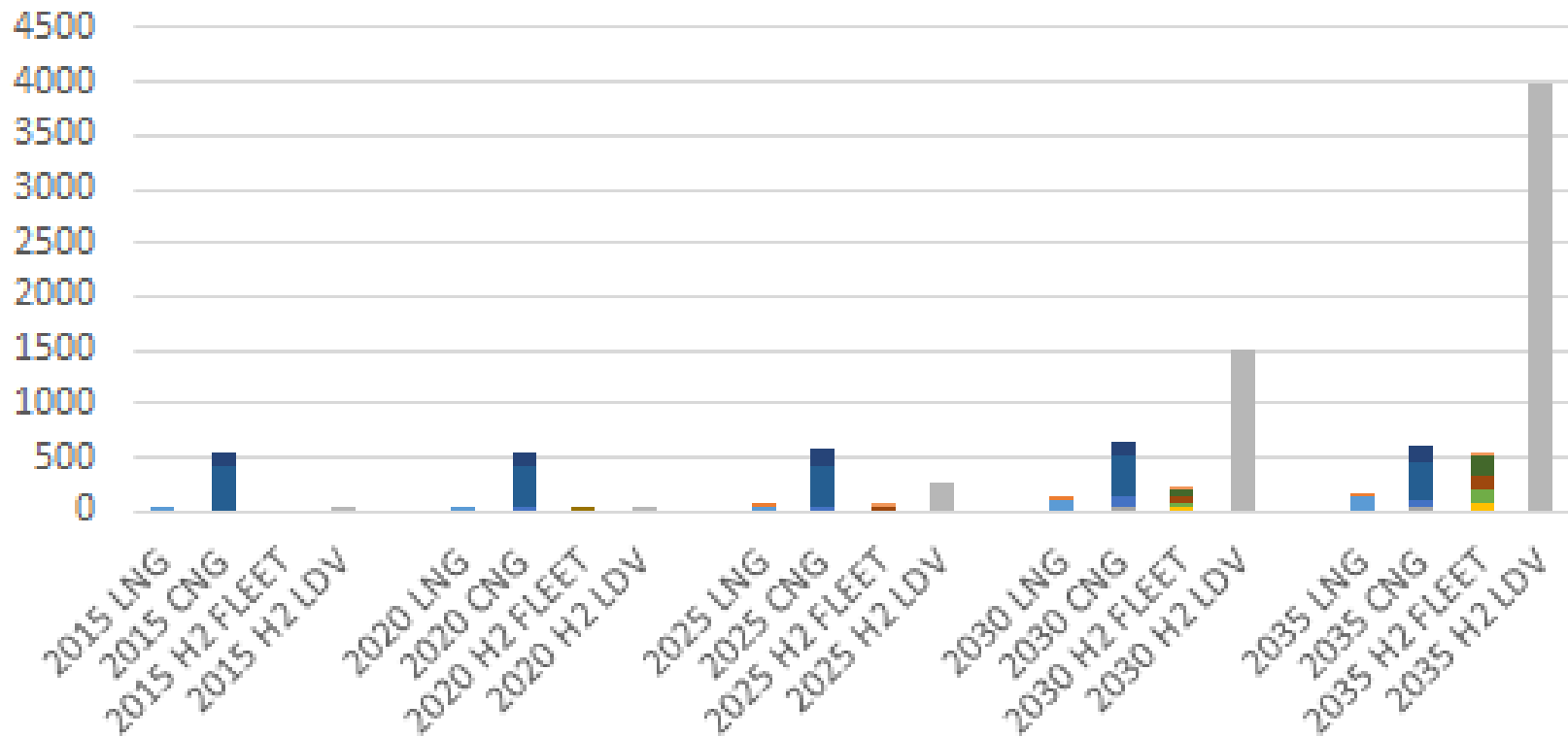


CA SCENARIO FOR NGVs, FCVs (LDVs, MD/HD): # LIGHT DUTY FCVS LARGEST BY FAR > 2025



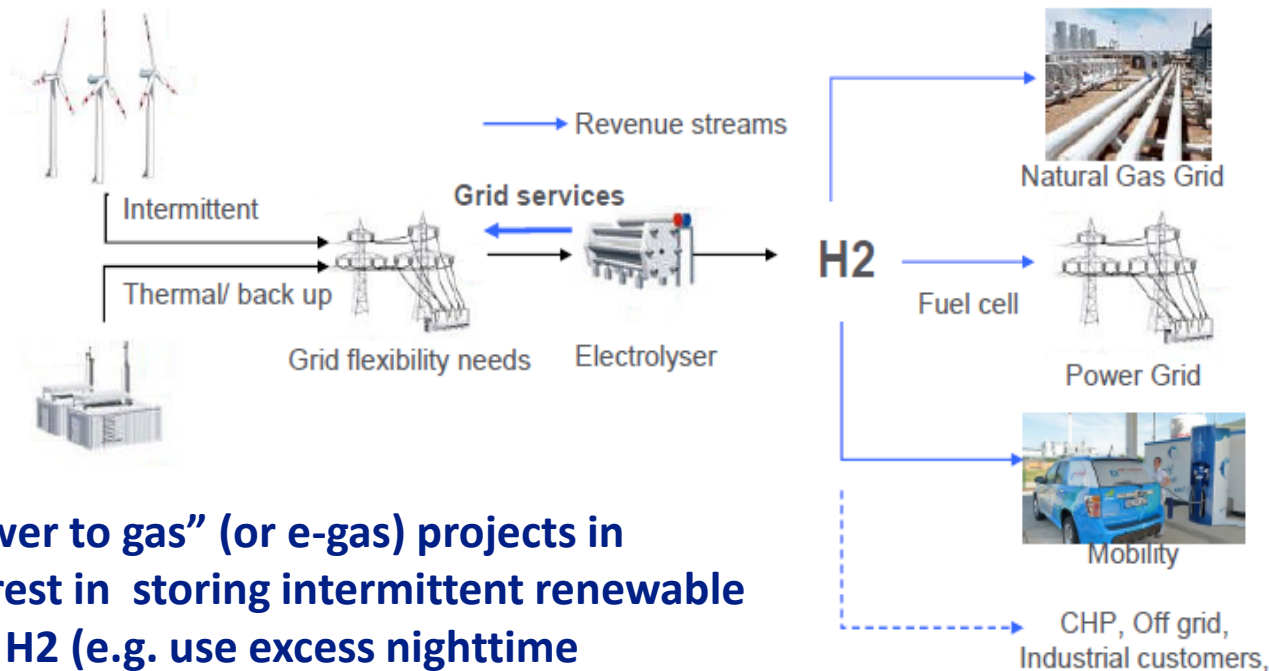
Many More Public H2 Stations Than Fleet Stations: Not Much Spatial Overlap For NG & H2 Stations Market Segmentation => Infrastructure Segmentation

California Scenario:
Number of stations for NG and H2 vehicles



POWER TO GAS? Studies => H2 Long Term Potential: Flexible Storage for Renewable Electricity

Versatility of Hydrogen is a key advantage for energy storage



Over 30 “Power to gas” (or e-gas) projects in Europe. Interest in storing intermittent renewable electricity as H2 (e.g. use excess nighttime electricity from wind to make electrolytic H2).

Source: P. E. Franc, “Financing Hydrogen Projects” Nov. 16, 2013, International Partnership for a Hydrogen Economy Conference, Seville, SPAIN

Potential Benefits of Blending Renewable H₂ into NG

- Electrolytic H₂ from curtailed renewables => market for excess solar or wind power.
- Reduces GHG emissions from NG (“greening” of NG by adding renewable H₂)
- Offer smooth transition from NG to H₂ by initially offering a NG-H₂ mixture
 - Begin transition to H₂ appliances on industrial and private scale
- Potential to lower transition cost of H₂ transportation by using existing pipeline infrastructure to distribute H₂
- Offer an immediate storage system
 - Storage referring to that H₂ within the pipelines, not external storage tanks

Technical issues for H₂/NG Blends -> NG system

- Blending relatively low concentrations (<5%–15% H₂ by volume), appears viable without significantly increasing risks of using the gas blend in end-use devices (such as household appliances), overall public safety, or the durability and integrity of the existing NG pipeline network.
- Appropriate blend concentration may vary significantly between pipeline network systems and natural gas compositions and must therefore be assessed on a case-by-case basis.
- Any introduction of a H₂ blend concentration would require extensive study, testing, and modifications to existing pipeline monitoring and maintenance practices (e.g., integrity management systems).
- Additional costs must be weighed against the benefit of providing a more sustainable and low-carbon gas product to consumers.

*Source: M. W. Melaina, O. Antonia, and M. Penev, "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues," Technical Report NREL/TP-5600-51995, March 2013. <http://www.nrel.gov/docs/fy13osti/51995.pdf>

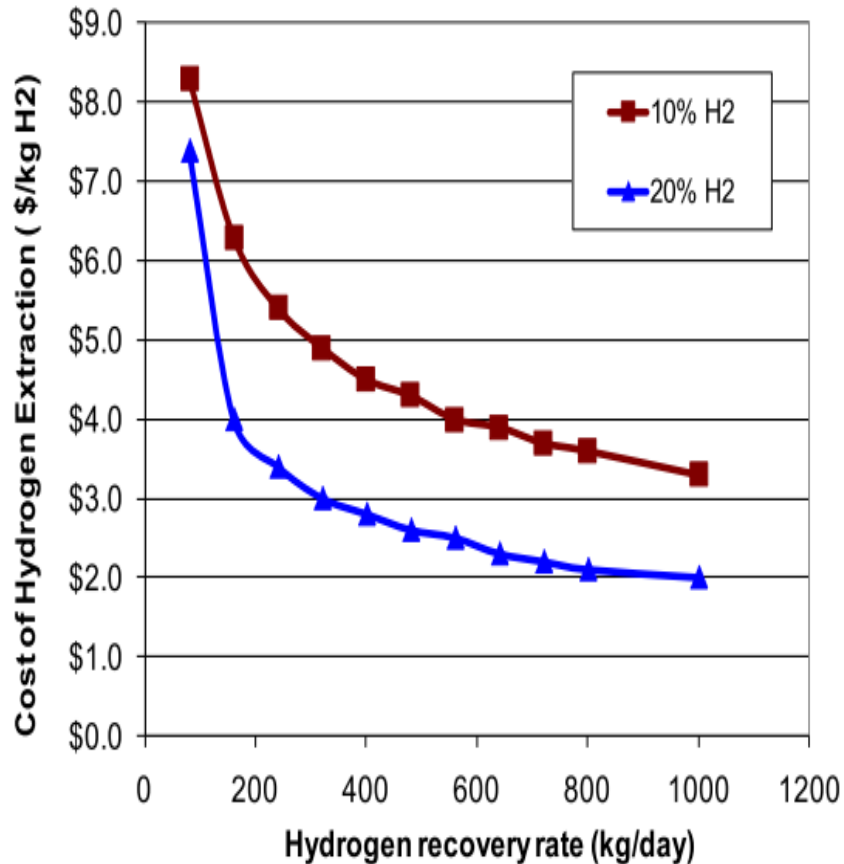
Using H₂/NG Blends in Transportation

- Hydrogen/natural gas blends can be directly used in modified internal combustion engine vehicles (ICEVs).
- Fuel cell vehicles, which are perhaps twice as energy efficient, require pure H₂ hydrogen.
- If pure H₂ can be separated from the blend downstream and used as fuel for a FCV, this significantly reduces well to wheel GHG emissions as well as SO₂, NO_x, and PM.
- However H₂ separation has costs and energy requirements which add to costs for providing pure H₂ for transport or industry applications via blends.

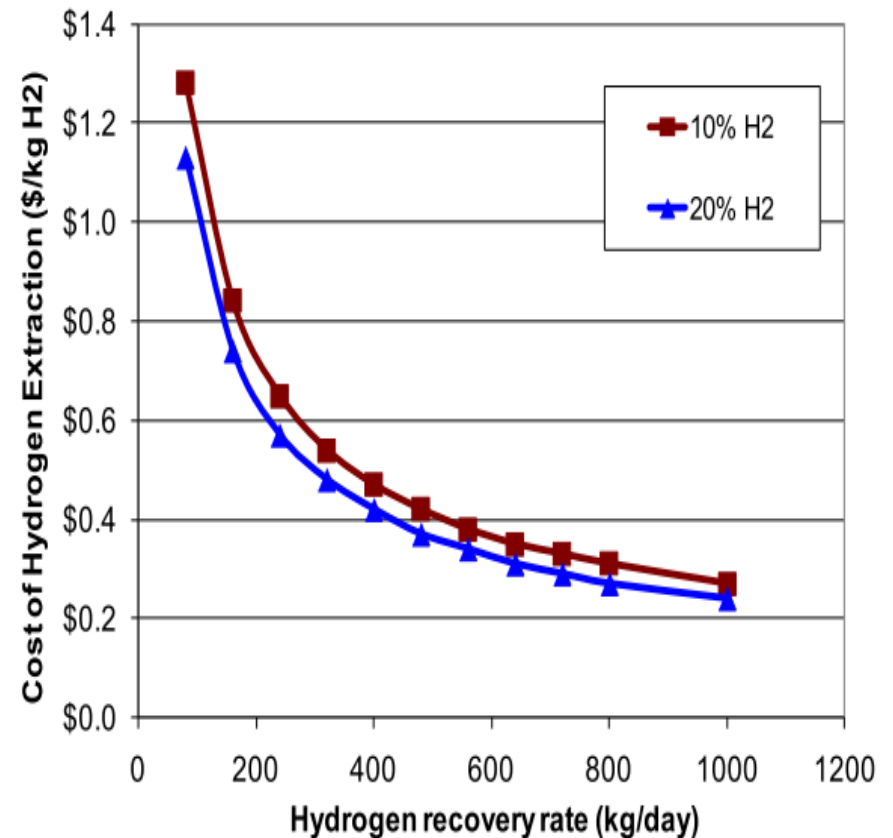
Separation Costs can Rival Delivered H2 costs (\$5-7/kg)

PSA Extraction at Pressure Step-down Station 300 to 30psi

At 300 psi distribution main



At pressure reduction facility



DTI (2011). Directed Technologies, Inc. (DTI)

Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues

Blending Renewable H2 w/NG: Carbon implications

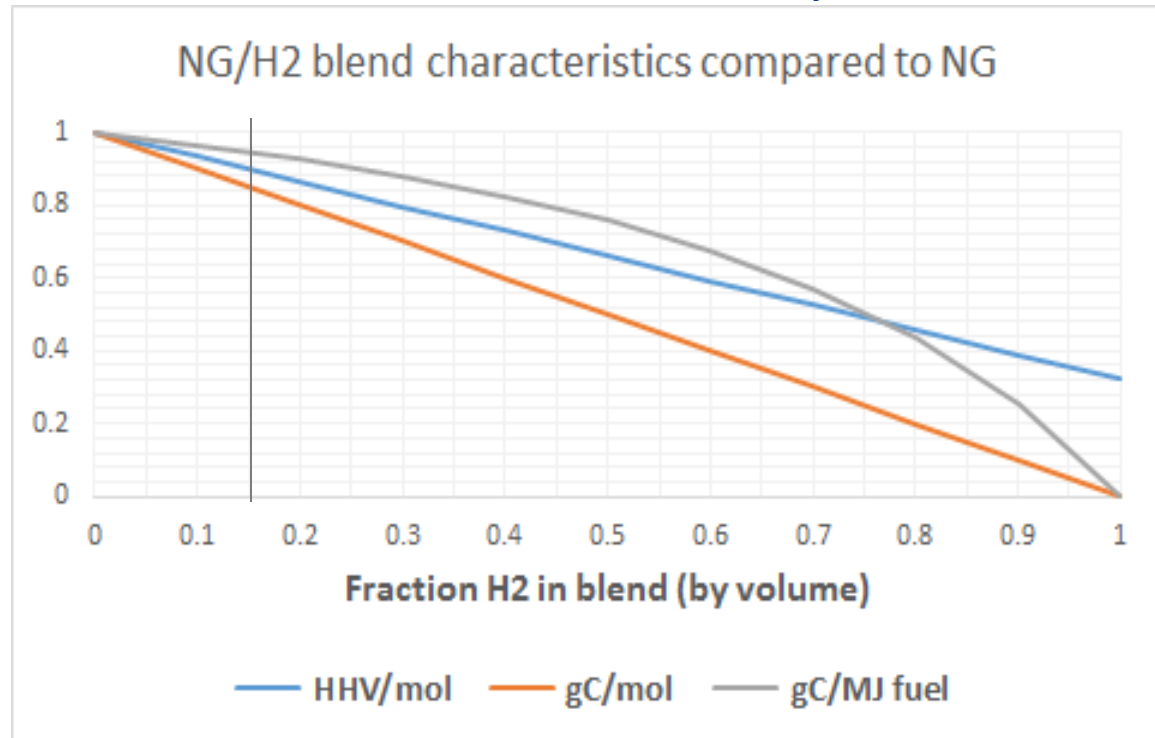
NG/H2 blends of up to 5-15% H2 by volume could be implemented without major changes to NG distribution and end-use systems.

Higher Heat value: fuel gases

- H2 = 286 kJ/mol
- NG = 889 kJ/mol
- 15%H2/85%NG = 799kJ/mol

Add 15% zero-C H2 to NG:

- Reduces gC/mol **15%**
- Reduces HHV/mol by **10%**
- Reduces gC/MJ fuel **5%**



Combusting NG/H2 blend as direct NG replacement offers C emissions reduction of 1.7-5%, with 5-15% zero-C H2 by volume.

Limits on Blending Strategy? Back of the envelope calc.

H2 from curtailed solar or windpower: How much?

- Denholm et al. NREL estimate 5-10% curtailed power in 50% renewable CA grid.
- Total CA grid annual average power ~60 GW.
- Annual average 3-6 GW curtailed power => 2.4-4.8 GW electrolytic H2 (80% eff)

NG Pipeline Capacity for H2 Blends

- Pipeline system delivers about 70 GW of NG (annual average basis)
- H2 blend limit about 1.7-5% on energy basis
- Allowed H2 flow about 1.2-.3.5 GW on annual average basis.
- Pipeline capacity for H2 < curtailed power available.

Can we make enough green H2 from curtailed power?

- In 2 degree world -> 10-20 million FCVs in CA by 2050, each requiring a flow of ~1 kW H2
- 10-20 GW of H2 needed to fuel FCVs.
- NG pipeline capacity to carry H2 is an order of magnitude lower than demand in low-C world. Plus need to separate H2 from to gain eff. benefit of FCVs.

In long term H2 Transport fuel at scale will need a pure H2 infrastructure

Conclusions

- We have examined several questions surrounding the idea that near to mid-term use of natural gas in transportation might help enable a transition to longer term use of hydrogen.
- Scenario analysis for using each fuel in various applications suggests that market, technical, economic and geographic/refueling network design factors will constrain the degree of overlap between H2 and NG.
- More research is needed to
 - Detailed case study to assess the potential for electrolytic H2 from curtailed power in California, and compare to other storage and H2 supply options.
 - Assess the suitability of California's NG pipeline system for use with H2 blends.

Jaffe, Amy Myers, Rosa Dominguez-Faus, Joan M. Ogden, Nathan C. Parker, Daniel Scheitrum, Zane McDonald, Yueyue Fan, Tom Durbin, George Karavalakis, Justin Wilcock, Marshall Miller, Christopher Yang (2017) The Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion to Near-Zero Transportation Technology. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-17-04



- To get the full “well to wheels” carbon reduction benefit of hydrogen and fuel cell vehicles, requires making hydrogen from zero carbon pathways, such as renewables.
- Power to gas using curtailed renewables has been suggested, but it is uncertain whether curtailed variable renewable energy would be a large enough resource to provide fuel for the large numbers of fuel cell vehicles needed for a 2 degree scenario. Future research is needed to clarify this question.
- In the near to mid-term, if we want to utilize the natural gas infrastructure with a greener fuel, biogas may be a better fit than hydrogen
- Ultimately, biogas resources won’t be able to deliver the magnitude of GHG reductions that H₂ could because of the smaller size of biogas resource, the higher efficiency of hydrogen fuel cell vehicles as compared to natural gas combustion engine vehicles, and abundant options for zero carbon H₂ production.
- This suggests that even if we pursue a near to mid-term strategy to “green” fossil natural gas by adding biogas (and perhaps green hydrogen up to a technical limit of 5-15% by volume) we will need to continue to build out a parallel H₂ infrastructure, so it would be ready to fuel growing numbers of zero emission vehicles.

Markets for H2 & NG Vehicles will naturally segment

- “Vehicle choice for commercial applications, (e.g. freight trucks & delivery vans) is driven by economics and business needs. These businesses are already on a path towards broad use of NG for trucks & vans.
- “In contrast, automakers expect that H2 fuel cell electric vehicles (FCEVs) will be adopted more broadly for personal transportation.
- “While there may be overlap in selected niches, such as buses or light duty fleet vehicles, current market and manufacturer signals indicate that H2 and NG will likely segment into different transportation application areas.”

Source: Final Report: Transitioning the Transportation Sector: Exploring the Intersection of Hydrogen Fuel Cell and Natural Gas Vehicles, September 9, 2014. American Gas Association, 400 N. Capitol St., NW, Washington, DC 20001. Organized in partnership by: Sandia National Laboratories, AGA and Toyota, in support of the U.S. Department of Energy. http://energy.gov/sites/prod/files/2015/02/f19/2015-01_H2NG-Report-FINAL.pdf

Safety

- Service lines typically limit the % blend of H₂ in regards to safety due to their enclosed environment
 - Should not exceed 20% blend
- Distribution mains can operate at up to 50% H₂ blend safely with only minor risks associated
- Main risk factors considered
 - Gas buildup
 - Not a problem at <50% blend. Buoyancy of H₂ offsets increased flow rate
 - Explosion in enclosed location
 - Service lines
 - Transmission risks
 - < 20% safe
 - > 20% service lines become dangerous
 - > 50% distribution mains become dangerous

Transmission Risk = frequency of pipe failure ×
Probability of ignition × consequence of fire

Transmission Risks

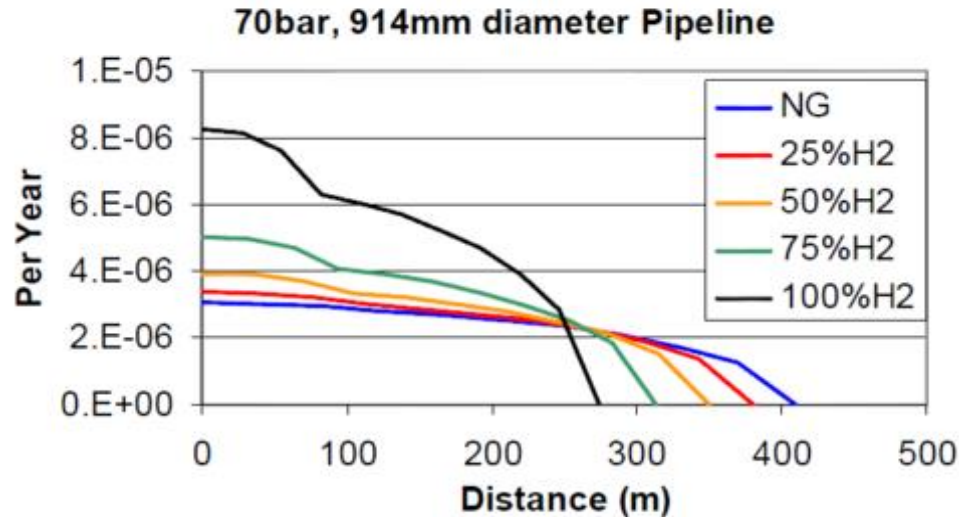
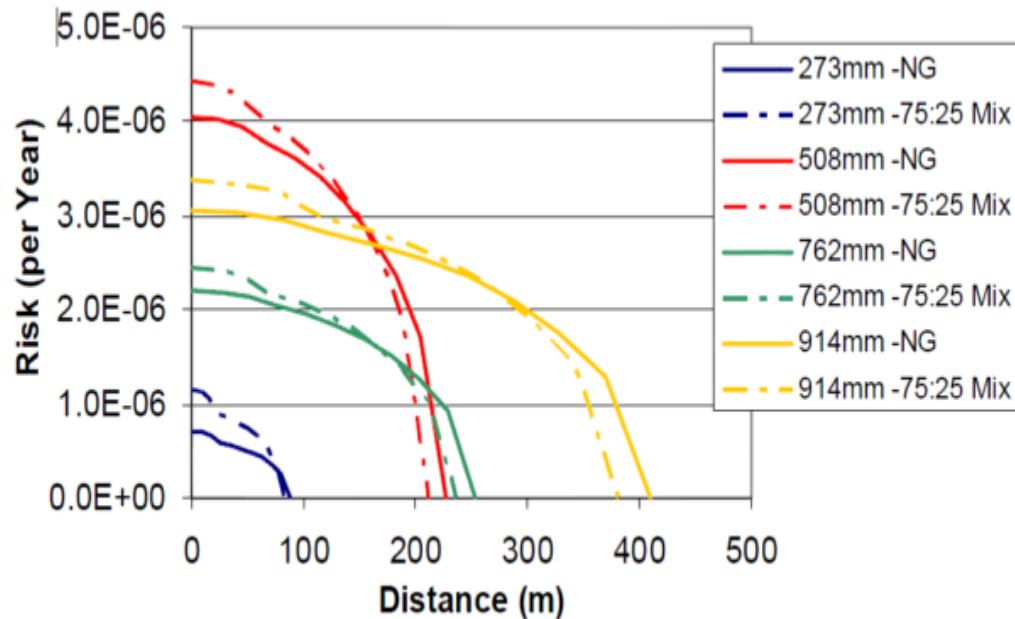


Figure 12. Risk to an individual per year as a function of distance from the pipeline.



Adding Hydrogen to the Natural Gas Infrastructure - Assessing the Risk to the Public - Lowesmith

Figure 13. Risk to an individual per year by adding hydrogen to the natural gas pipeline: UK data.

Operator Safety Risk

Table 13. Risk Assessment for Distribution Services at Three Hydrogen Levels

Failure Mode	Probability ^a (%)	Risk Factor				Overall Risk			
		NG ^b	< 20% H ₂ ^c	20 to 50% H ₂ ^c	>50% H ₂ ^c	NG ^b	< 20% H ₂ ^c	20 to 50% H ₂ ^c	>50% H ₂ ^c
Corrosion	21.64	16.77	26.77	26.77	36.77	6.11	9.75	9.75	13.39
Material Defect	11.16	35.53	45.53	45.53	55.53	2.48	3.18	3.18	3.88
Natural Force	3.40	22.95	42.95	42.95	42.95	1.94	3.64	3.64	3.64
Excavation	24.90	50.00	70.00	90.00	100.00	7.69	10.77	13.85	15.39
Other Outside Force	3.95	10.00	20.00	20.00	30.00	0.19	0.37	0.37	0.56
Equipment	12.71	30.00	40.00	40.00	50.00	2.02	2.70	2.70	3.37
Operation	2.57	30.00	40.00	40.00	50.00	0.76	1.01	1.01	1.27
Other	19.66	10.00	20.00	20.00	30.00	2.16	4.32	4.32	6.48
Total	100.00	205	305	325	395	23	36	39	48

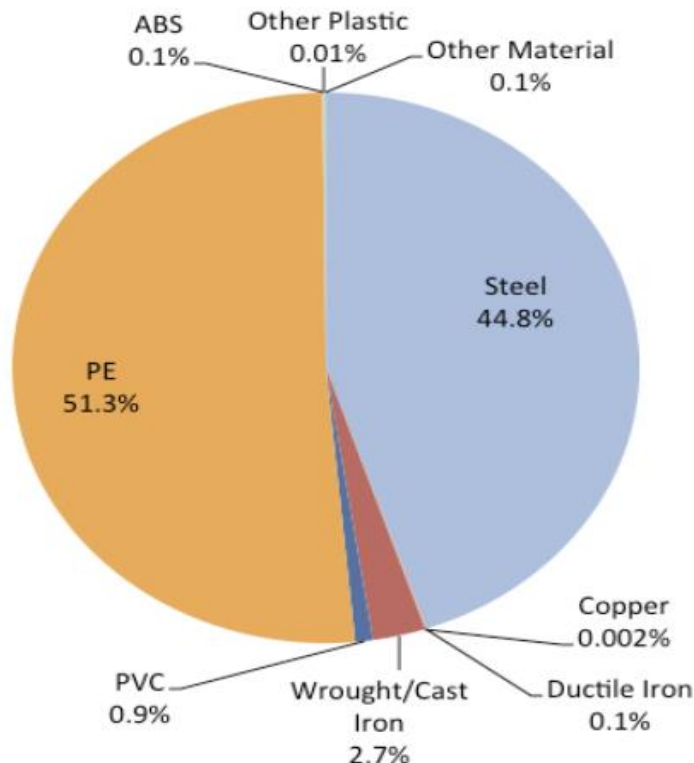
Change in RF : 5 – Minor , 10 – Moderate, 20 – moderately significant, 40- significant, 50 – significant to a high degree
 Risk Ranking: 0 – None, 30 – Moderate, 50 - Severe

DOT 2007 Annual Distribution Data – Pipeline Hazards

Material Durability

- High pressure H₂ can degrade certain materials found in NG pipelines (Hydrogen embrittlement)
 - Cracking**
 - Blistering**
 - Hydride formation**
 - Loss of tensile strength**
- H₂ pressure, purity, temperature, material microstructure
- Polymer pipelines typically perform better with H₂ blends

Polymers	Compatibility
Polyethylene	Good
Polyvinyl Chloride	Good
Natural Rubber	Fair
Butyl Rubber	Good
Silicone Rubber	Fair
Neoprene (CR)	Good
Buna S (SBR)	Good
Viton	Good
Buna N (NBR)	Good



NaturalHy Projects-GTI led Durability Testing
Chemical Resistance of Thermoplastics Piping
Materials – Plastic Pipe institute

Leakage

- Permeation rate of H_2 is 4 to 5 times higher than methane through polymer pipes and 3 times higher through steel and iron pipes.
- In polymer pipes, most gas loss occurs through pipe walls. In metal pipes, loss occurs primarily at threads
- 414,830 miles of polyethylene pipes of < 2 inches = 40million cubic feet per year at 20% H_2
- Gas leakage is considered to be absolutely *economically* insignificant

Leakage

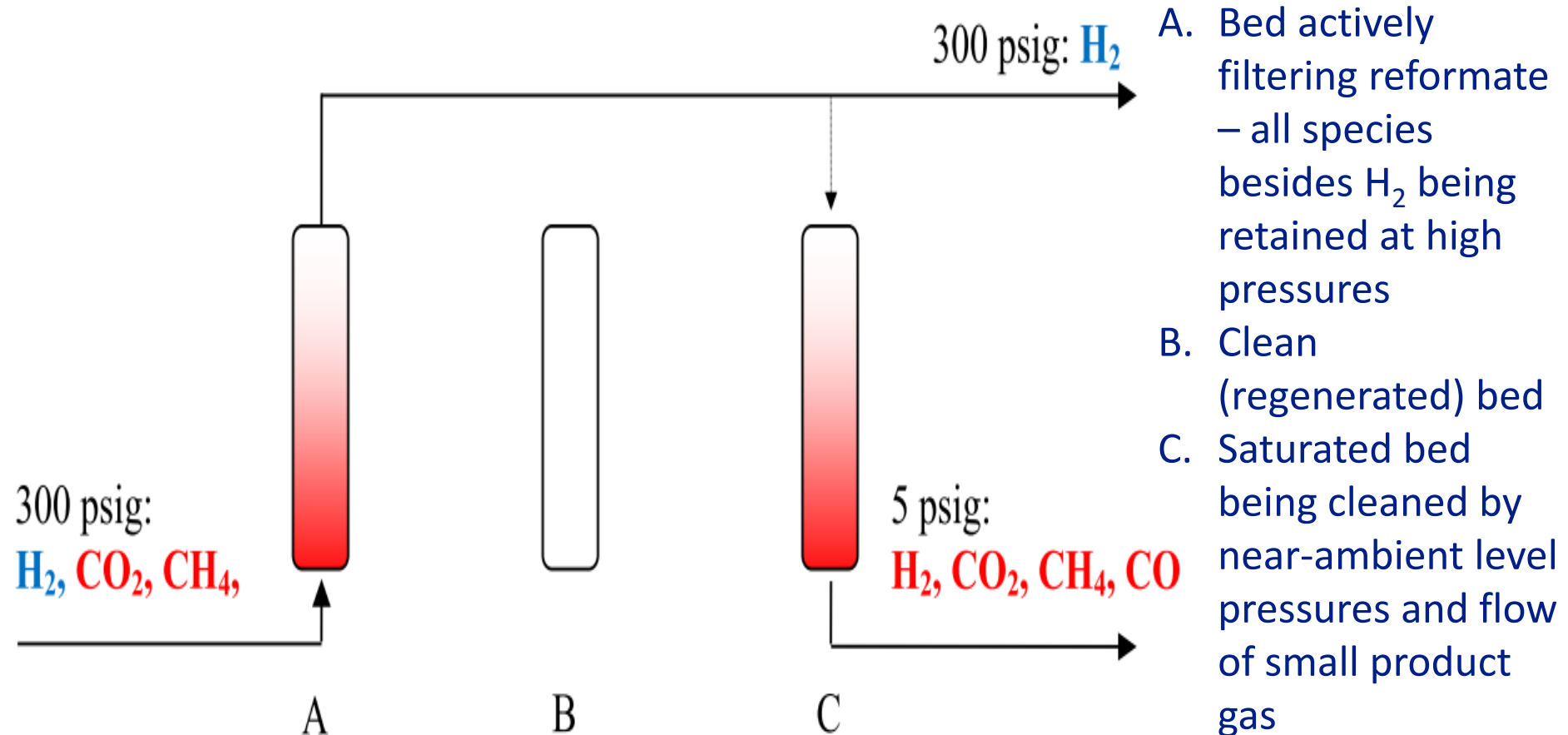
Table 17. The Calculated Gas Loss Rate (ft³/mile/year) Based on Literature Data for HDPE Pipes at the Operating Pressures of 60 psig, 3 psig and 0.25 psig*

Hydrogen Content	At 60 psig			At 3 psig			At 0.25 psig		
	H ₂	CH ₄	Total	H ₂	CH ₄	Total	H ₂	CH ₄	Total
0%	0.0	49.4	49.4	0.0	2.5	2.5	0.0	0.2	0.2
10%	32.9	44.5	77.4	1.6	2.2	3.9	0.1	0.2	0.3
20%	65.9	39.5	105.4	3.3	2.0	5.3	0.3	0.2	0.4
50%	164.7	24.7	189.4	8.2	1.2	9.5	0.7	0.1	0.8
100%	329.3	0.0	329.3	16.5	0.0	16.5	1.4	0.0	1.4

NaturalHy Projects-GTI led Durability Testing

Pressure Swing Absorption (PSA) Extraction

- Occurring at pressure step-down station



Pressure Swing Absorption Cost Factors

- Filtering beds
 - Size of necessary bed \propto percent composition of impurities (all non-H₂ agents)
 - Regeneration time \propto percent composition of impurities (all non-H₂ agents)
 - Higher purity H₂ can be achieved by more frequent cycling of beds
- Valving and flow controls
- Packing materials
- Compressor (\approx 40% of capital cost of extraction for 10% H₂ mixture)
 - Not necessary at pressure step-down station
- H₂ loss
 - \approx 20% for a 10% H₂ mixture in commercial grade NG blend at 300-psi stepdown

Is NG a Bridge to H2? Overarching Question

- If we build a near term NG fueling infrastructure, could it be "re-used" or at least provide a springboard for H2 infrastructure later on?

H2 Blending Questions

- Will addition of hydrogen affect the integrity and safety of the natural gas delivery system? For example, will hydrogen “embrittle” pipeline or storage materials designed for use with natural gas?
- How will energy flow rate be affected by addition of hydrogen?
- Will natural gas end-use systems such as CNG vehicles, home appliances or heating systems still operate safely and efficiently with hydrogen blended in?
- How much will blending add to overall system cost?
- What are the potential greenhouse gas benefits of blending “green hydrogen” with natural gas?

Can NGV Infrastructure Help Launch H2 FCVs?

- Infrastructure location may be driven by different factors, timing for each fuel/market.
- NG truck stations may be located in different places than early H2 stations.
- Our scenario does not envision a major switch from CNG to hydrogen in fleet trucks and buses by 2035. New capacity for hydrogen is added rapidly after 2025. The main issue is adding hydrogen supply, rather than repurposing CNG equipment or overbuilding NG stations for future H2 compatibility.
- In longer term >2035, there is a shift toward H2 from low carbon pathways, but this can happen in a planned transition.
- Not a lot of stranded CNG stations in our scenario.

Our results suggest that trying to utilize the existing NG system to deliver H2 transportation fuel is not promising in the near to mid-term for several reasons.

- Hydrogen and natural gas are being developed for different transportation markets, where there is limited technical or spatial overlap. The main overlap for H2 appears to be in truck or bus fleet applications now served by CNG.
- However, even for similar applications, converting NG refueling stations to hydrogen is problematic. Repurposing LNG infrastructure for hydrogen is not technically possible. Converting some components in CNG refueling stations to hydrogen is technically possible, but expensive and economically unattractive.
- Transporting H2/NG blends in the NG pipeline grid, appears technically possible at modest fractions of 5-15% hydrogen by volume, but requires careful case by case assessment, could be expensive and does not enable major reductions in well to wheels GHG emissions, when used as a transport fuel, unless hydrogen can be separated from the blend and used in a highly efficient fuel cell vehicle.
- If H2/NG blending were implemented, a host of measures would be required to assess the suitability of each natural gas network for hydrogen and assure safety and efficient operation .